(12)

DEPARTMENT OF THE NAVY
DTNSRDC

THEORY OF POWER AUGMENTED RAM LIFT AT ZERO FORWARD SPEED

by

Roger W. Gallington and Harvey R. Chaplin

AVIATION AND SURFACE EFFECTS DEPARTMENT

Report ASED 365

February 1976

DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

BETHESDA MARYLAND 20084

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
Report ASED 365

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
6 THEORY OF POWER AUGMENTED RAM LIFT AT ZERO FORWARD SPEED.

5. TYPE OF REPORT & PERIOD COVERED
9 Interim ~~Report~~.

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
10 Roger W./Gallington ~~and~~ Harvey R./Chaplin

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
David W. Taylor Naval Ship R&D Center
Bethesda, Maryland 20084

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
Program Element 63534N
Task Area SSH15002
Work Unit 1612-008

11. CONTROLLING OFFICE NAME AND ADDRESS
Commander
Naval Air Development Center
Warminster, Pennsylvania 18974

12. REPORT DATE
11 Feb[redacted]976

13. NUMBER OF PAGES
12

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
14 DTNSRDC/ASED-365

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

12 13p.

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release: distribution unlimited

16 SSH15 17 SSH15002

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Ground Effect
Powered Lift
Ram Wing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Recent experiments by Huffman and Jackson demonstrated the possibility of an air cushion operating mode for an aircraft with low aspect ratio end-plated wings wherein the propulsion system is mounted forward of the wing and exhausted into the space between the wing and the ground to generate high pressures for wing lift at zero forward speed. Gallington has derived two-dimensional potential flows relevant to this phenomenon,

(continued on reverse side)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

387695 LB

but applying to larger ratios of propulsive jet area to leading edge air gap area (height of wing above ground times wing span) than were employed in the experiments. In this report, simple momentum theory is applied to obtain performance estimates for a range of jet area ratios from zero to the limiting cases of the potential flow solutions. Reasonable agreement with experiment is found, suggesting that two-dimensional flow models may give useful estimates of the performance potential of such systems. It is found that, under conditions such that a large fraction of the propulsion system thrust is recovered as useful propulsive thrust, the ratio of lift to thrust is very sensitive to the jet area ratio and optimum performance is obtained for jet area ratios approaching unity. Additional experiments are needed, covering the full range of jet area ratios, to evaluate the practical potential of power augmented ram lift systems.

TABLE OF CONTENTS

	Page
ABSTRACT	1
ADMINISTRATIVE INFORMATION	1
INTRODUCTION	1
MOMENTUM THEORY	2
CONCLUSIONS	6

LIST OF FIGURES

Figure 1 - Potential Flow Classes	3
Figure 2 - Underfilled Duct Class	3
Figure 3 - Comparison with Experiment	8

Table 1 - Formulas for 2D Analyses	7

NOTATION

Symbol	2D Definition	Assumed 3D Equivalent
c	Wing chord	Wing area
h	Height of wing lower surface above ground	Area: (height of wing lower surface) X (wing span)
t_1	Thickness of incoming jet upstream of wing	Cross-sectional area of incoming jet upstream of wing
t_2	Thickness of departing jet downstream of wing	Cross-sectional area of departing jet downstream of wing
β	Angle at which reentrant portion of jet leaves measured from original jet velocity vector	Angle at which reentrant portion of jet leaves measured from original jet velocity vector
P_c	Pressure exerted on wing lower surface in midchord region	Pressure exerted on wing lower surface in midchord region
q_j	Dynamic pressure of undisturbed jet	Dynamic pressure of undisturbed jet
C_p	Pressure coefficient: P_c/q_j	Pressure coefficient: P_c/q_j
T_j	Jet thrust: $2q_jt_1$	Jet thrust
T_{net}	Net thrust: T_j minus drag force on wing	Net thrust: T_j minus drag force on wing
C_T	Thrust recovery coefficient: T_{net}/T_j	Thrust recovery coefficient: T_{net}/T_j
L	Lift on wing	Lift on wing

ABSTRACT

Recent experiments by Huffman and Jackson[1] demonstrated the possibility of an air cushion operating mode for an aircraft with low aspect ratio end-plated wings wherein the propulsion system is mounted forward of the wing and exhausted into the space between the wing and the ground to generate high pressures for wing lift at zero forward speed. Gallington[2] has derived two-dimensional potential flows relevant to this phenomenon, but applying to larger ratios of propulsive jet area to leading edge air gap area (height of wing above ground times wing span) than were employed in the experiments. In this report, simple momentum theory is applied to obtain performance estimates for a range of jet area ratios from zero to the limiting cases of the potential flow solutions. Reasonable agreement with experiment is found, suggesting that two-dimensional flow models may give useful estimates of the performance potential of such systems. It is found that, under conditions such that a large fraction of the propulsion system thrust is recovered as useful propulsive thrust, the ratio of lift to thrust is very sensitive to the jet area ratio and optimum performance is obtained for jet area ratios approaching unity. Additional experiments are needed, covering the full range of jet area ratios, to evaluate the practical potential of power augmented ram lift systems.

ADMINISTRATIVE INFORMATION

This investigation was authorized and funded by the Naval Air Development Center under Project SSH15, Program Element 63534N, and Work Unit 1-1612-008.

INTRODUCTION

The experiments of Reference 1 demonstrate an interesting potential for generating wing lift at zero speed (and presumably at low speed) by directing the propulsion system exhaust into the space between the wing and the ground. For example, lift forces more than six times greater

---

[1]Huffman, J. K. and C. M. Jackson, Jr., "Investigation of the Static Lift Capability of a Low-Aspect-Ratio Wing Operating in a Powered Ground Effect Mode," NASA TM X-3031 (Jul 1974).

[2]Gallington, R. W., "Sudden Deceleration of a Free Jet at the Entrance of a Channel," DTNSRDC Departmental Report ASED 350 (Jan 1976).

than the propulsion system thrust were generated at zero speed while simultaneously recovering about 60 percent of the propulsion system thrust as useful propulsive thrust.

This phenomenon might prove to be of great practical interest in future water-based aircraft design by providing means for avoiding high hydrodynamic drag during takeoff and high impact loads during takeoff and landing. Also, an air cushion cruise mode might be of interest to provide surface mobility over short ranges or under sea state conditions which prevented takeoff.

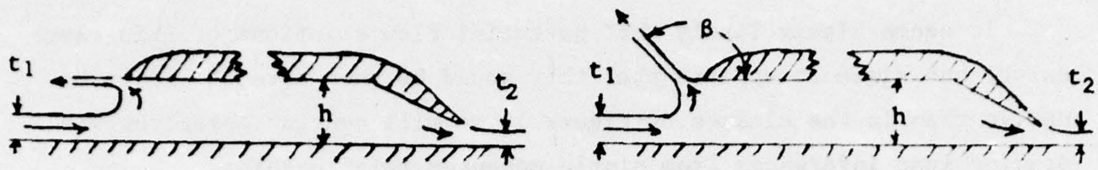
The available experimental data cover very limited ranges of the geometric parameters which appear to be important. It is desired to construct theoretical flow models which would provide insight into the phenomenon, estimates of performance limitations, and guidance for further experiments.

Two-dimensional potential flow solutions obtained in Reference 2 appear to be definitely relevant, and in fact may represent "optimum" cases of the power augmented ram lift phenomenon in certain important senses. However, they cover a range of jet area ratios which are not directly comparable to the experiments. Moreover, the experiments (and probably designs of practical interest as well) involve flows which are definitely <u>not</u> two-dimensional.

The step taken in this report will be to develop two-dimensional theoretical estimates which can be directly compared with the available experimental data in order to tentatively confirm that two-dimensional analyses may have a useable degree of applicability to practical cases.

MOMENTUM THEORY

In Reference 2, potential flow solutions were obtained for two classes of flows which will be referred to here as the "filled duct" class and the "overfilled duct" class, as illustrated in Figure 1.



(a) Filled Duct (b) Overfilled Duct

Figure 1 - Potential Flow Classes

These solutions have the property that the pressure recovery coefficient $C_p = 1 - (t_2/h)^2$ (which can be derived very simply from one-dimensional fluid mechanics principles). For a given value of C_p, the minimum admissible value of jet area ratio t_1/h corresponds to the filled-duct class. In other words, the filled-duct class is a limiting case of the overfilled duct class. To investigate cases of still smaller jet area ratios, we must adopt a modified flow model. The simplest, in the sense of involving fewest theoretical difficulties, is illustrated in Figure 2.

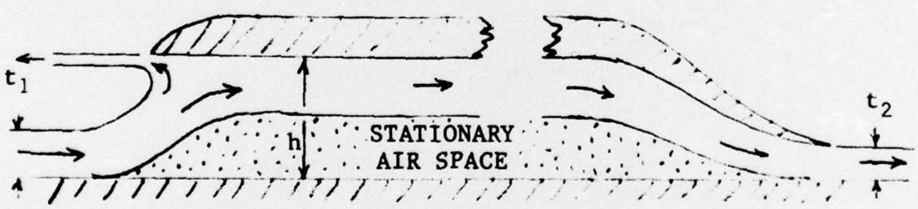


Figure 2 - Underfilled Duct Class

The incoming jet is assumed to curve away from the ground as it approaches the wing and to stagnate against the bottom of the wing near the leading edge splitting into one branch which reemerges forward parallel to the ground (as in the filled duct case) and a second which follows the bottom surface of the wing rearward until, near the trailing edge, it is led back into a tangent (nonstagnating) contact with the ground before reaccelerating to the original jet velocity at the trailing edge.

It seems highly likely that potential flow solutions of this class exist, but since it appears that they would be much more difficult to derive than in the classes of Figure 1, we will content ourselves with drawing some inferences from simple momentum relationships.

From one-dimensional fluid mechanics we can conclude that the thickness of the jet along the lower surface of the wing at midchord is $t_2/\sqrt{1-C_p}$ and its velocity is $V_j\sqrt{1-C_p}$. A momentum balance between a vertical plane upstream of the wing and one through the midchord thus takes the form

$$2q_j t_1 + 2q_j(t_1 - t_2) = P_c h + 2q_j t_2\sqrt{1-C_p}$$

$$C_p = 4t_1/h - 2(t_2/h(1+\sqrt{1-C_p}) \qquad (1)$$

whereas this expression is rather awkward to solve for C_p directly, numerical solutions are readily extracted.

The thrust relationships are the same as in the filled-duct class, i.e.,

$$T_j = 2q_j t_1$$

$$T_{net} = 2q_j t_2 - 2q_j(t_1 - t_2)$$

$$C_T = 2t_2/t_1 - 1 \qquad (2)$$

There is a further difficulty in comparing these results to the experimental results of Reference 1 in that those experiments employed a compressed-air jet from a thin rectangular nozzle located many nozzle thicknesses upstream of the wing. The jet arriving at the wing is thus a fully-developed turbulent jet with a velocity distribution which is nonuniform and not precisely known. However, assuming momentum is conserved in the experimental jet, this problem can be

circumvented by working with force and momentum relationships rather than pressure relationships.

Noting that

$$L = q_j C_p c \text{ (assuming } c >> h)$$

$$T_j = 2 q_j t_1$$

then

$$L/T_j = \frac{C_p}{2t_1/h} \frac{c}{h}$$

and the quantity

$$\frac{L}{T_j} \frac{h}{c} = \frac{C_p}{2t_1/h} \qquad (3)$$

(which is readily evaluated numerically for given values of C_T and t_2/h from Equations (1) and (2)) lends itself to qualitative comparison with the available experimental data.

This comparison is made in Figure 3. It can be seen that, for the cases of moderate flap deflection, the agreement is reasonably good. Caution is advisable in drawing conclusions from this agreement since we are comparing uniform-jet, two-dimensional theory with distinctly nonuniform-jet, three-dimensional experiments. Also, the quantity h, which in the theory has been defined as distance from the ground to a parallel flat lower surface of the airfoil, is not directly definable for the experimental airfoil, which has a convex lower surface. (For plotting the experimental data, h was taken to be the height of the theoretical trailing edge of the airfoil above the ground.) Nevertheless, the two-dimensional theory seems to provide a reasonable basis for a tentative and cautious assessment of the potential of power augmented ram lift systems pending acquisition of a broader experimental data base.

Even if these uncertainties regarding applicability of two-dimensional analysis to practical cases are ultimately resolved, there are two further effects which clearly need to be taken into account: (1) viscous effects, expecially the additional thrust loss due to friction between the jet and the wing, and (2) effect of nonuniform pressure, expecially near the leading and trailing edges of the wing. (The theory assumes uniform pressure of magnitude $C_p q_j$ over the entire lower surface for purposes of computing lift, which is admissable only if h/c is very small.

The relationships available for two-dimensional analyses are summarized in Table 1.

CONCLUSIONS

- Theoretical relationships developed in Reference 2 for estimating the performance of power augmented ram lift systems have been extended to include all possible values of the jet area ratio.

- These relationships have been found to be in reasonable agreement with experimental results reported in Reference 1 (which are confined, however, to a limited range of rather small jet area ratios).

- While this agreement with experiment is hardly conclusive, it seems reasonable to use the theoretical relationships (with due caution and appropriate corrections) for preliminary studies of power-augmented ram lift systems, pending the availability of a more complete experimental data base.

- Experiments to provide a more complete data base are needed.

TABLE 1 - FORMULAS FOR 2D ANALYSES

Quantity	Filled Duct*	Overfilled Duct*	Underfilled Duct
t_2/h	independent variable ≤ 1		
β	$180°$	independent variable ≥ 0, $\leq 180°$	$180°$
t_2/t_1	$\dfrac{4t_2/h}{(1+t_2/h)^2}$	$\dfrac{2(1-\cos\beta)\,t_2/h}{1-(2\cos\beta)\,t_2/h+(t_2/h)^2}$	independent variable $\geq \dfrac{4t_2/h}{(1+t_2/h)^2}$, ≤ 1
t_1/h	$\longleftarrow (t_2/h)/(t_2/t_1) \longrightarrow$		
C_p	$1-(t_2/h)^2$		$1-\left[t_2/h+\sqrt{(1+t_2/h)^2-4t_1/h}\right]^2$
C_T	$2t_2/t_1 - 1$	$(1-\cos\beta)\,t_2/t_1+\cos\beta$	$2t_2/t_1 - 1$
$\frac{L}{T_j}\frac{h}{c}$ #	$C_p/(2t_1/h)$ $= \sqrt{2(1-C_T)}$	$C_p/(2t_1/h)$	$C_p/(2t_1/h)$

*From Reference 2.

#Note that the formulas assume $h/c \ll 1$. The effect of finite h/c is probably to reduce L/T_j somewhat.

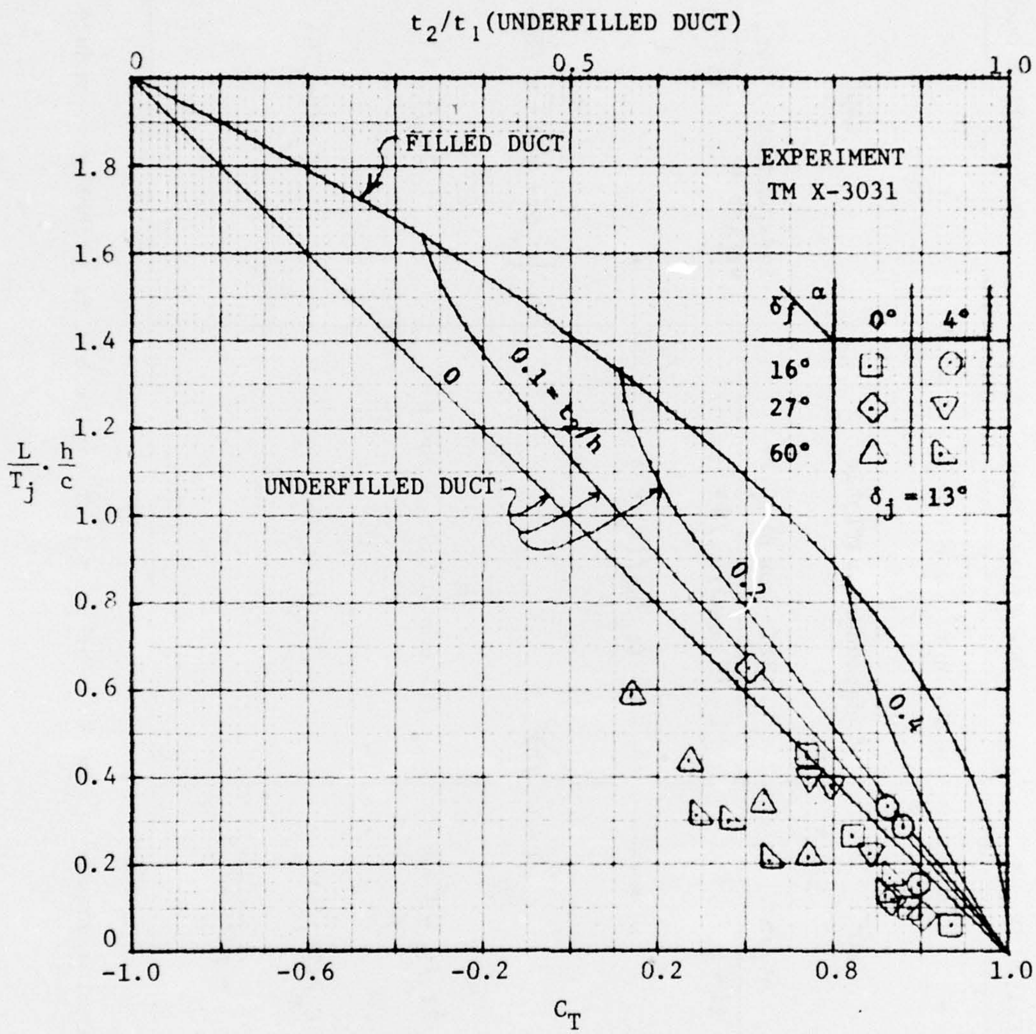


Figure 3 - Comparison with Experiment

DTNSRDC ISSUES THREE TYPES OF REPORTS

(1) DTNSRDC REPORTS, A FORMAL SERIES PUBLISHING INFORMATION OF PERMANENT TECHNICAL VALUE, DESIGNATED BY A SERIAL REPORT NUMBER.

(2) DEPARTMENTAL REPORTS, A SEMIFORMAL SERIES, RECORDING INFORMATION OF A PRELIMINARY OR TEMPORARY NATURE, OR OF LIMITED INTEREST OR SIGNIFICANCE, CARRYING A DEPARTMENTAL ALPHANUMERIC IDENTIFICATION.

(3) TECHNICAL MEMORANDA, AN INFORMAL SERIES, USUALLY INTERNAL WORKING PAPERS OR DIRECT REPORTS TO SPONSORS, NUMBERED AS TM SERIES REPORTS; NOT FOR GENERAL DISTRIBUTION.